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THESIS

EFFECTS OF SLEEP DEPRIVATION ON U.S. NAVY WATCHSTANDER PERFORMANCE ONBOARD THE INDEPENDENCE CLASS LITTORAL COMBAT SHIP (LCS 2)

by

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September 2013

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In spite of the incredible technologic advances over the history of the U.S. Navy, the human operator continues to be the most important part of any system. The Littoral Combat Ship (LCS) concept proposed to reduce the number of sailors required to run a ship by leveraging new technologies. While the consequences of this manning decision are debatable, the effect of fatigue on a ship's crew and their ability to perform is not.

Using archival sleep data obtained from LCS-2, this thesis assessed the relationship between fatigue and crew member performance on the Psychomotor Vigilance Test and the Switching Test. While the regression analyses did not yield statistically significant results, the chi-square test showed that a significant departure occurred from the sleep obtained by LCS-2 crew members and the 480 minutes of daily sleep recommended in the NSWW.

The effect of fatigue on a ship's crew requires further research and a course of action is presented in the recommendations of this thesis that would help researchers obtain the necessary data for proper sleep study analyses.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANAM	Automated Neuropsychological Assessment Metrics
ASCM	Anti-Ship Cruise Missiles
B.A.C.	Blood Alcohol Concentration
BEQ	Bachelor’s Enlisted Quarters
FAST	Fatigue Avoidance Scheduling Tool
HFACS	Human Factors Analysis Classification System
LCS 2	Independence Class Littoral Combat Ship
LCS	Littoral Combat Ship
NPS	Naval Postgraduate School
NREM	Nonrapid Eye Movement
NSWW	Navy Standard Workweek
PVT	Psychomotor Vigilance Testing
REM	Rapid Eye Movement
RCO	Readiness Control Officer
TBI	Traumatic Brain Injury
U/A	Unauthorized Absence from Duty
VBSS	Vessel Boarding Search and Seizure

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EXECUTIVE SUMMARY

The Littoral Combat Ship (LCS) and its manning concept represent a giant leap forward in the U.S. Navy's Surface Fleet manning concepts. The LCS has attempted to leverage advanced technologies to reduce the number of man-hours needed to operate the ship, and by extension, reduce the number of crew members required to operate the ship. The current LCS model has a core Blue/Gold crew concept modeled after the U.S. Navy's submarine fleet. This plan transitions LCS to a "3-2-1" crewing model in which each ship would be deployed for a 16-month period during which two 40-man crews would rotate every four months (O'Rourke, 2013). While this manning concept continues to be debated, preliminary reports noted that the 40-man crew suffered severe fatigue and degradation in crew readiness and safety (Capaccio, 2013).

Previous research has demonstrated that sailors on current U.S. Navy ship classes (destroyers, frigates, and cruisers) receive less sleep than recommended by the Navy Standard Workweek (NSWW). The findings on destroyers showed an average weekly sleep debt of 4.9 hours, on frigates the weekly sleep debt was an average of 9.0 hours, and on cruisers, the sleep debt was an average of 5.9 hours per sailor (Haynes, 2007; Green, 2009; Mason, 2009). This chronic sleep debt leads to severe fatigue and impacts the ability of the crew to perform their duties effectively thereby degrading the ship's overall combat readiness.

The Office of Naval Research (ONR), has been conducting an interdisciplinary study of sailor performance, the Performance Shaping Functions (PSF) project. Over the course of this research, the PSF team of scientists has been given access to crewmembers of LCS-1 and LCS-2 in order to quantify the effects of motion on sailor performance. The current thesis effort examined archival data for the crew of LCS-2 (USS Independence) to determine if their sleep was related to their performance. Crewmembers' sleep was collected through wrist-worn actigraphy. Cognitive performance was measured by using the Switching Test and the Psychomotor Vigilance Test (PVT). Both these tests have been validated in previous laboratory research and have shown sensitivity to individual test participant fatigue (Basner & Dinges, 2011; Reeves et al., 2007).

To explore the relationship between fatigue and performance, this thesis addresses three questions. (1) Are daily sleep duration (in minutes), daily sleep efficiency, daily predicted effectiveness, or day on which the tests were taken related to PVT response speed (1/reaction time) or Switching Test performance? (2) What is the deviation between sleep duration (as determined by actigraphic recordings) and the daily recommended sleep allotment of 480 minutes mandated in the NSWW? (3) Does predicted effectiveness from the Fatigue Avoidance Scheduling Tool (FAST) provide a valid estimate of an individual's PVT response speed?

Results showed that on average, sailors onboard LCS-2 received 371 minutes (6 hours and 11 minutes) of the 480 minute (8-hour) recommendation in the NSWW. Of the 27 sailors in this study, only one received more sleep than recommended; however, data for this sailor was recorded on only four days of the 10-day test period. The results from the Switching Test showed that throughput (the rate of correct responses) increased from 19.8 on day one to 35.1 on day 10. There was a clear learning effect present on the Switching Test and the effect of that learning overshadowed any decrement caused by fatigue and sleep debt. PVT reaction time remained relatively consistent with the average ranging from 235 to 240 ms; the lack of baseline PVT reaction times prevented comparisons from being made.

The archival data were analyzed using regression models, ANOVA, and chi-square tests to find relationships between the sleep and performance results. A chi-square test was conducted on the actigraphic sleep and the daily recommended sleep allotment from the NSWW. The final step in the analysis used multiple regression to explore how PVT response speed was predicted by the effectiveness measure provided by FAST.

Results from this research effort showed that none of the expected predictors varied systematically with the measures of performance. The results of the chi-square test suggested that a significant departure occurred from the expected daily sleep time of 480 minutes outlined in the NSWW. Finally, the lack of significant results from the regression analysis did not allow for the construction of a meaningful predictive model between FAST predicted effectiveness and PVT response speed.

While these results appear counterintuitive, there were significant flaws in the study design that led to missing and incomplete data collection. The lack of a baseline for PVT reaction time did not allow for a within subjects comparison. The learning effect on the Switching Test was overwhelming; if the Switching Test is used again it should be administered for seven consecutive days prior to the beginning of data collection. Also, the schedule and number of PVTs administered should be tightly controlled. Finally it is imperative that accurate schedule information be collected from watch bills, plans of the day/week, as well as watch station and watch rotation of each individual participant.

In spite of the lack of significant results from the regression models, it was clear that the crew of LCS-2 is not getting adequate sleep. Suggestions for follow-on research are included that would help researchers obtain the necessary data for proper sleep study analyses.

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I. INTRODUCTION

A. BACKGROUND

> Why when I PCS [transfer] does the government want me to only drive 350 miles and get 8 hours of sleep but when I drive a BILLION DOLLAR Warship I only need 4?
>
> —From the unofficial Junior Officer Protection Association (JOPA) Facebook Page

During his January 15, 2013, address at Naval Postgraduate School (NPS), retired Navy Captain David Marquet, bestselling author, and former commander of the submarine USS Santa Fe, entertained the audience with a story of a sailor who incurred an unauthorized absence from duty (U/A) during Captain Marquet's command tour. The sailor was affectionately nicknamed "Sled-Dog" by fellow crewmembers, due to his tireless work ethic and ability to continue working without sleep. The story: During a brief port visit in San Diego, CA, Sled-Dog failed to report for duty and was listed U/A, which was unusual for such a stellar performer and Captain Marquet knew that the story involved more than an overindulgent sailor in Tijuana. As the story unfolded, it was discovered that the Sled-Dog had simply checked into the Bachelor's Enlisted Quarters (BEQ) for some much deserved sleep. When Captain Marquet began to dig for information and "rewind the clock" on Sled-Dog's schedule, he found that the sailor had gone from watch to cleaning to drills to watch to drills to cleaning. The Captain had a simple question, "How far back do I have to rewind the clock to find out when this sailor last slept?" The answer did not please him and was simply unacceptable, "Maybe 30–40 hours, Sir!"

While an entertaining story, it is all too often the "norm" for sailors and officers onboard United States (U.S.) Navy ships and submarines. Creating realistic schedules to meet the increasing demands of accelerated operational tempos and decreasing resources, while balancing the sanity and health of the ship's crew, is more important than at any time in the Navy's 237-year history. Budget cuts and the seemingly never-ending need to

do more with less drives ships crews to the brink of failure and greatly decreases overall combat readiness.

From the founding of the U.S. Navy and the ships of John Paul Jones and Commodore John Barry, the Navy has been a place in which the term “sleep when you’re dead” has been ingrained in the culture of surface warfare officers and the sailors under their command. Guzzling coffee and “manning up” became the tradition and the corporate knowledge of how to manage watch and work schedules was passed from one generation of sailor to the next with no thought or worry as to the long- or short-term effects on a sailor’s health or cognitive and physical readiness. Notwithstanding the incredible technological advances that the Navy has achieved since its founding on October 13, 1775, the demands on a sailor’s time and the need to be awake and alert have not wavered. The need to balance work, watch, training, drills, meetings, and sleep have always come at the expense of a sailor’s sleep schedule and the Navy’s combat readiness.

A critical need exists for an intervention in this self-destructive cycle. One suggested intervention method is to take a macroergonomic view of the culture that perpetuates crew fatigue. Hendrick has described macroergonomics as the optimization of organizational and work systems design through consideration of relevant personnel, technological, and environmental variables and their interactions (Hendrick & Kleiner, 2002).

Previous efforts at the macroergonomic level have included studies that have examined the Navy Standard Workweek (NSWW) versus actual sleep patterns of U.S. Naval sailors on destroyers (Haynes, 2007), frigates (Green, 2009), and cruisers (Mason, 2009). Additional efforts have been conducted that examined the proper management of crew schedules and alternative watch rotations (Roberts, 2012; Yokeley, 2012). This thesis continues these efforts by examining the effects of sleep deprivation on cognitive performance functions onboard the Navy’s newest class of surface vessel, the Littoral Combat Ship (LCS).

B. OBJECTIVES

This research effort is an analysis of performance issues related to sleep deprivation and fatigue aboard the Independence Class Littoral Combat Ship (LCS 2). The unique manning structure of the LCS platform is based on the Blue/Gold crew models of the U.S. submarine fleet, and represents a major shift in Surface Fleet manning concepts. The LCS has attempted to leverage advanced technologies to significantly reduce the number of man hours needed to operate the ship. However, even with the advanced technologies onboard, it is likely that the reduced manning will lead to increased crew fatigue and a heightened potential for human error during operations. Previous studies on fatigue and sleep deprivation have indicated that sleep deprivation and fatigue affect information processing (Heisinger, 2009; Hursh, 2005; Killgore et al., 2007; Lamond & Dawson, 1999; Miller & Firehammer, 2007; Miller, Matsangas, & Kenney, 2012; Nilsson et al., 2005). In line with previous work, this study applies regression and other statistical analysis to determine if a relationship exists between an LCS 2 crewmember's archival sleep data and that crewmember's performance on Psychomotor Vigilance Testing (PVT) and Automated Neuropsychological Assessment Metrics (ANAM) testing.

C. SCOPE, LIMITATIONS, ASSUMPTIONS

The scope and limitations of this research effort are that the actigraphy (sleep) data, PVT scores, and the Switching Test results were collected solely from one of the two LCS platforms within the U.S. Navy. While similarities exist in the manning structure and planning on both LCS platforms, this thesis deals with data taken on LCS 2 (USS INDEPENDENCE). The assumptions are that the unique manning structures of both LCS platforms are equal. If this assumption holds, then the research on one platform will translate across the whole LCS program. While recognized and reported mechanical and performance issues with both LCS platforms do exist, those issues are outside the scope of this research effort.

D. THESIS ORGANIZATION

Chapter I describes the background of the U.S. Navy's culture of chronic sleep deprivation and introduces a suggested intervention through macroergonomic principles. Chapter II contains a literature review of crew fatigue, sleep, sleep studies at NPS, the NSWW, the unique LCS manning concept, the Fatigue Avoidance Scheduling Tool (FAST), PVT, and ANAM. Chapter III describes the methodology and data collection techniques used to quantify sleep quality and performance. The results and implications of reduced quality sleep on cognitive performance within the LCS platform are discussed in Chapters IV and V. Finally, the conclusions and recommendations are presented in Chapter VI.

II. LITERATURE REVIEW

A. FATIGUE

Multiple studies of human error have pointed to fatigue as a primary causal factor in maritime incidents/accidents (Rothblum, 2000). The Human Factors Analysis Classification System (HFACS) lists fatigue as a primary precondition under “adverse physiological states,” and has three specific nano-codes that list fatigue as a causal factor in mishaps attributed to human error (HFACS, 2005). Several high-profile incidents have been linked to fatigue including the Exxon Valdez oil spill in Alaska (Root Cause Analysis, 2009), the USS Radford colliding with the merchant ship Saudi Riyadh (Allen, Farwell, & Smith, 2005), the USS Port Royal grounding off Hawaii (Cole, 2009), and the collision of the submarine USS Hartford with the amphibious transport dock USS New Orleans in the Straits of Hormuz (Scutro, 2009). These incidents were all linked to poorly managed schedules and crew fatigue.

A 1999 study of the U.S. Coast Guard Cutter Munro, during a patrol from Tokyo, Japan to Pearl Harbor, noted severe issues with crew fatigue and the need for proper schedule management (Comperatore, Bloch, & Ferry, 1999). The U.S. Coast Guard Guide for Managing Crew Endurance Risk Factors warns that chronic fatigue can challenge an individual’s resolve to exercise regularly, eat nutritious foods, and obtain sufficient sleep (Mandler, 2006).

These studies all point to the same conclusion: the Navy needs an improved approach to dealing with the complexities of ship’s schedules and crew fatigue. This study seeks to help identify issues specific to the LCS platform that can address that need.

B. SLEEP

The effects of sleep deprivation have been likened to the effects of alcohol consumption, with cumulative time without sleep having an equivalent blood alcohol concentration (B.A.C.). Simply stated, being sleep-deprived is similar to being intoxicated (Dawson & Reid, 1997; Lamond & Dawson, 1999). While no sane

commanding officer would allow an intoxicated officer to take control as officer of the deck, the Navy routinely sends sleep deprived officers and crew to stand critical watches, which places those ships and crews in jeopardy.

In addition to the comparisons to B.A.C., sleep deprivation has been shown to decrease executive decision making and cognitive function after just a single night of sleep deprivation (Nilsson et al., 2005). McKenna et al. (2007) found that 23 hours of sleep deprivation altered decisions involving risk significantly; subjects were more likely to take a risk for a perceived gain when sleep deprived. A second study found that not only cognitive and executive functioning become impaired, moral judgment was also found to be affected by sleep deprivation (Killgore et al., 2006).

While an individual's general health, fitness level, stress level, and workload are all linked to their fatigue level, the root cause of fatigue is a lack of sufficient sleep. Sleep has been described as a "physiologically driven event" that is "central to our ability to perform physical and cognitive tasks" (Miller & Firehammer, 2007). Human sleep has been shown to occur in two overarching categories (shown in Figure 1), rapid eye movement (REM) and nonrapid eye movement (NREM), with NREM sleep further divided into five sub-categories from Stage 0 (awake) to Stage 4 (the deepest part of the sleep cycle), (Miller et al., 2008). Sleepers cycle through these stages over the course of approximately 8 hours. Each stage has been shown to be critical to repairing the mind and body while sleeping (Miller & Firehammer, 2007).

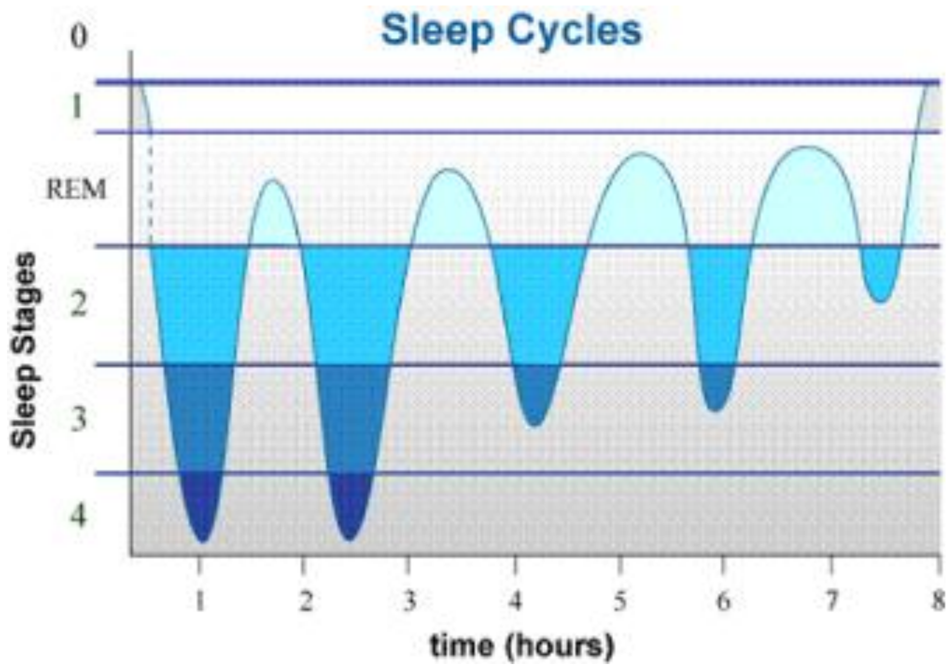

Figure 1. Sleep stages in the normal adult human (From Miller, Matsagas, & Shattuck, in press)

The 8-hour sleep cycle requirement is an average with some people needing slightly more sleep, and some needing slightly less. Research on Navy ships has shown that the average amount of daily sleep varies widely between ship classes. sailors rarely enjoy prolonged periods of contiguous sleep but rather must make do with short naps combined with one longer sleeping period. Table 1 shows summary data from several sleep studies conducted on various ship classes and ship employment types. The data show a wide disparity exists between the amount of sleep humans need to achieve maximum readiness and the amount of sleep obtained by sailors in these shipboard environments.

Table 1. Sleep studies by author and year, ship class, ship employment, and average hours of sleep obtained

Author and Year	Ship Class	Ship Employment	Average Hours of Sleep + (STDEV)
Nguyen (2002)	CVN	Op Enduring Freedom	6.28 (1.50)
Haynes (2007)	DDG	Training	7.27 (1.03)
Mason (2009)	CG x 2	Training	5.58 (1.92)
Green (2009)	FFG	Training	6.71 (NR)
Brown (2012)	LCS	Training	7.36 (2.63)

Previous research has shown that the unique operational environment of a ship at sea can cause interruptions in the ability to stay asleep and prevents sailors from achieving the full restorative physiological effects of a full night's sleep (Brown, 2012; Calhoun, 2006). Calhoun (2006) pointed to the effects of constant motion and vibration of a ship at sea stating that it "puts the human body in a constant state of aggravation." Brown (2012), who found a significant decrease in the sleep quality by sailors when their ship is at-sea, supported this viewpoint by citing the increased activity counts in the Actigraphy data across all participants during at sea periods. These interruptions, as well as those from alarms, from machinery noise, ringing phones, fellow crew members, and countless other sources, make it difficult to achieve proper restful sleep.

C. PREVIOUS SLEEP STUDIES AT NPS

The issue of crew fatigue has plagued sailors since man first took to the sea. During the Peloponnesian War from 413–404 B.C.E., Greek ships were forced to remain near land to go camp ashore for adequate food and sleep (Sacks, Murray, & Brody, 1995). In the U.S. Navy, only incremental and uncoordinated efforts have been made to correct the issue of crew fatigue. In a NPS thesis, Stolgitis (1969) advocated changing from the traditional four hours on, eight hours off (4/8) to a six hours on, 12 hours off (6/12) rotation to facilitate better sleep schedules, and provide "one full night of sleep" (eight hours) every third day. This suggestion failed to receive support in a 1981 study of sleep patterns on nuclear submarines (Beare et al., 1981). The submarine sleep study

found that the 6/12 rotation led to “fragmented sleep of generally less than 6 hours in duration.”

Efforts to correct the issue of fatigue within the Navy were at a standstill until the early 2000s when Dr. Nita Shattuck, in conjunction with NPS thesis students, began to renegotiate the Navy’s “sleep when you’re dead” culture. Table 2 lists these efforts chronologically.

Table 2. NPS theses relating to work schedule, sleep, and/or fatigue

Author	**Year**	**Title**
Ngyuen	2002	The Effects of Reversing Sleep-Wake Cycles on Sleep and Fatigue on the Crew of USS John C. Stennis
Baldus	2002	Sleep Patterns in U.S. Navy Recruits: An Assessment of the Impact of Changing Sleep Regimens
Kenney & Neverosky	2004	Quantifying Sleep and Performance of West Point Cadets: A Baseline Study
Osborn	2004	An Analysis of the Effectiveness of a New Watchstanding Schedule for U.S. Submarines
Andrews	2004	The Relationship Between Sleep Regimen and Performance in United States Navy Recruits
Pearson	2004	Circadian Rhythms, Fatigue, and Manpower Scheduling
Miller	2005	Sleep and Predicted Cognitive Performance of New Cadets during Cadet Basic Training at the United States Military Academy
Archibald	2005	Effects of Noise, Temperature, Humidity, Motion and Light on the Sleep Patterns of the Crew of HSV-2 SWIFT
Solberg	2006	Sleep Patterns of Naval Aviation Personnel Conducting Mine Hunting Operations
Godfrey	2006	Optimizing Daytime Short Sleep Episodes to Maximize Performance in a Stressful Environment
Haynes	2007	A Comparison between the Navy Standard Workweek and the Actual Work and Rest Patterns of U.S. Navy sailors
Lazzaretti	2008	HSI in the USN Frigate Community Operational Readiness and Safety as a Function of Manning Levels
Maynard	2008	Marine Aviation Weapons and Tactics Squadron One (MAWTS-1): Sleep, Fatigue, and Aviator Performance
Besheny	2009	Analysis of Navy Flight Scheduling Methods Using FlyAwake
Green	2009	A Comparative Analysis between the Navy Standard Workweek and the Actual Work/Rest Patterns of sailors Aboard U.S. Navy Frigates

Author	Year	Title
Heisinger	2009	Association between Driver-Reported Sleep and Predicted Levels of Effectiveness Based on the Fatigue Avoidance Scheduling Tool
Mason	2009	A Comparative Analysis between the Navy Standard Work Week and the Work/Rest Patterns of sailors Aboard US Navy Cruisers
Nikitin	2011	Fatigue Effects on Optimal Manning: A Comparison of Ashore and Afloat Cognitive Performance and Sleep Quality
Brown	2012	Maritime Platform Sleep and Performance Study: Evaluating the SAFTE Model for Maritime Workplace Application
Roberts	2012	Analysis of Alternative Watch Schedules for Shipboard Operations: A Guide for Commanders
Yokeley	2012	Effects of Sleep Deprivation on U.S. Navy Surface Ship Watchstander Performance using Alternative Watch Schedules

These efforts speak to the broad spectrum of the negative effects of fatigue and can be sorted into three major categories: manning levels, fatigue effects, and schedule management. Green (2009), Haynes (2007), Mason (2009), and Nikitin (2011) addressed the need for proper manning levels and the associated issues with the NSWW. Haynes (2007) focused on the NSWW issues onboard destroyers. Green (2009) continued these efforts on frigates, and Mason (2009) on cruisers. All these efforts found that sailors stationed on sea duty routinely worked longer hours and had less sleep than outlined in the NSWW. Nikitin (2011) continued these efforts by examining the differences between afloat and ashore environments, and found a significant decrease in the amount and quality of sleep received by sailors at sea, which supported the findings of the previous research efforts.

Andrews (2004), Ngyuen (2002), and Pearson (2004) addressed specific negative effects of sleep deprivation and fatigue on human performance. Ngyuen (2002) conducted research on the aircraft carrier USS John C. Stennis, and found that sailors had difficulty adjusting to night-shift work at sea, especially those who were working on the flight deck and exposed to sunlight immediately prior to sleeping. Pearson (2004) found a correlation between sleep deprivation and a decrease in volunteer lab technicians' work performance after only one week. Andrews (2004) examined the sleep regimen of U.S.

Navy recruits during recruit training. He found that increasing the average hours of sleep from six hours per night to eight hours per night led to an 11 percent increase in average recruit test scores.

Baldus (2002), Heisinger (2009), Roberts (2012), and Yokeley (2012) discussed the management of crew and watch schedules. Baldus (2002) examined the impact of shifting the time personnel slept rather than increasing the amount of sleep. He found that in younger sailors, this shift in timing of sleep aligned more closely with their natural sleep needs. A similar report of U.S. Army Basic Combat Trainees conducted at Fort Leonard Wood, MO found that by simply shifting the sleep schedule of the new recruits to match their natural biological sleep patterns, their performance improved in all training environments (Miller et al., 2010). Heisinger (2009) examined an archival database of large truck mishaps using FAST and found a correlation between increased fatigue and a higher percentage of mishaps. Roberts (2012) examined archival data contained in a survey of crew members satisfaction with a 3/9 watchbill from the cruiser USS San Jacinto. He used FAST to compare the predicted effectiveness of various watch rotations and schedules and found that with four section watchbills, the three hours on, nine hours off (3/9) schedule provided the highest level of predicted performance. For three section watchbills, the 4/8 was best, and for two section watchbills, the best schedule was 12/12. Roberts' (2012) findings were supported by Yokeley (2012) who examined the use of the 3/9 schedule onboard the destroyer USS Jason Dunham, and found that the 3/9 schedule was preferred by the crew.

These efforts have all demonstrated through scientific methods that sleep is indeed essential to combat readiness in the Navy, as well as our fellow services. The empirical evidence collected through these studies represents a giant leap forward in the effort to combat crew fatigue and represents a truly coordinated assault on the issue. This thesis continues these efforts with the aim of helping to improve the Navy's watch standing and manning policies with the specific focus on the LCS Class.

D. NAVY STANDARD WORK WEEK

The NSWW is outlined in OPNAVINST 1000.16K (NAVY TOTAL FORCE MANPOWER POLICIES AND PROCEDURES) and is the primary document used to determine the enlisted manpower needs of individual Naval units. Appendix C of the 1000.16K instruction details the NSWW for afloat units allotting 56 hours of sleep a week (equating to eight hours a day), 56 hours for watch standing (eight hours a day), and 14 hours (two hours a day) for additional work. An additional 11 hours a week is factored in for unique military duties and training, which brings the total hours of duty/work per week at sea to 81. Multiple studies have shown that sailors routinely exceed the NSWW in hours worked per week and routinely receive less than eight hours of sleep per day (Green, 2009; Haynes, 2007; & Mason, 2009). Haynes (2007) found that on average, enlisted sailors on an Arleigh Burke class guided missile destroyer (DDG), worked 11.71 hours more than allotted by the NSWW. Green (2009) repeated Haynes study on a Ticonderoga class guided missile cruiser (CG) and found that enlisted sailors worked on average 9.90 hours more than allotted by the NSWW. Green (2009) also repeated a similar study on an Oliver Hazard Perry class frigate (FFG) and found that enlisted sailors worked an average of 20.24 hours per week more than the NSWW and slept an average of 8.98 hours per week less than the NSWW. The findings by Green (2009) are of significant note to this study as the LCS has been touted as the replacement platform for the FFG class in the U.S. Naval Fleet (Pyatt, 2013). Figure 2 summarizes the data from these studies, with figures rounded to the nearest tenth.

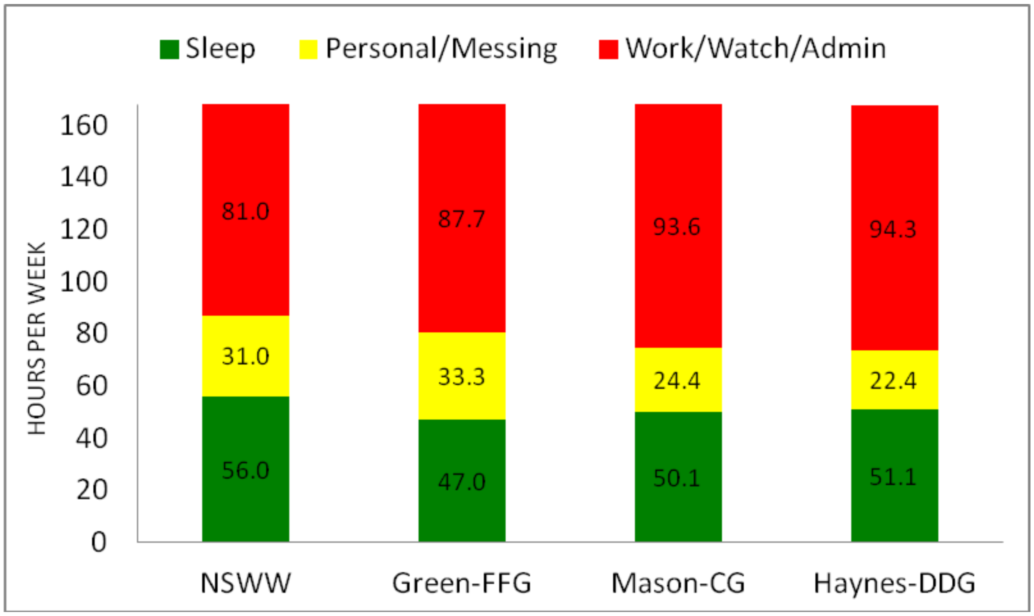

Figure 2. NSWW versus findings (From Green, 2009; Haynes, 2007; & Mason, 2009)

E. LCS MANNING

No ship program in recent Naval history has received more critical and unfavorable reviews than the LCS. Widely published issues have been mentioned concerning the cracking of the superstructure on the LCS 1 and corrosion due to insufficient insulation between the aluminum hull and steel water jet propulsion components on the LCS 2 (O'Rourke, 2013). These maintenance and manufacturing issues are outside the scope of this thesis. Issues associated with the unique manning structure of the LCS platform and its effect on crew fatigue and performance are the focus of this research effort.

The LCS represents an entirely new manning concept for surface vessels. From the inception of the LCS program, the goal was to leverage new technology and reduce/optimize manning to "the maximum extent possible" (Work, 2012). The current LCS model has a core Blue/Gold crew of 40 sailors each. The Navy plans to transition further to a "3-2-1" crewing model in which a LCS would be deployed for 16-months periods, and crews would rotate on and off deployed ships every four months (O'Rourke,

2013). Additionally, each LCS will have a "module detachment" of 15 sailors, and an aviation detachment of 25 sailors. The module and aviation detachments are "on-demand" and are not part of the permanent ship's company.

The manning of the LCS continues to be debated at the highest levels of the U.S. Navy. A recent report leaked to the media, prepared by Rear Admiral Samuel Perez, the Acting Assistant Deputy Chief of Naval Operations, was critical of LCS manning (Capaccio, 2013). In the report, Perez stated that currently on the LCS, "the minimal-manning level and subsequent fatigue result in significant operational and safety impacts, with notable degradation of crew readiness, performance levels, and quality of life" (Capaccio, 2013).

The leaked report prepared by Admiral Perez (known throughout the Navy as the OPNAV report) provides evidence that crew members interviewed on the LCS stated "fatigue levels set in on the third day of normal operations" (Capaccio, 2013). These reports are in line with a 2010 interview with then commanding officer of the USS Freedom (LCS 1) "Blue Crew," Commander Kris Doyle, in which he stated that life on the LCS was "grueling but manageable" and further that he averaged about "four to six hours of sleep every 24 to 48 hours" (Jean, 2010). In the same interview, Commander Doyle stated that crew members averaged "about six hours of rest" each day (Jean, 2010).

To address some of the known LCS manning issues, the Navy added 21 sailors to the LCS 1 for her maiden deployment in March 2013 (O'Rourke, 2013). The additional bodies may not be the optimal solution as adding sailors required the Navy to sacrifice space onboard the LCS needed to store additional food and supplies (O'Rourke, 2013). In the book, *The Mythical Man-Month*, author Fred Brooks offers "Brooks' Law," which suggests that if a job takes one man 10 months, it will not necessarily take 10 men one month to complete the same job (McCain, 2006). Brooks argues that by adding new personnel to a task, productivity may actually decrease as experienced personnel take time away from task completion to train new personnel, which thus decreases overall productivity in the short term.

Although the LCS was conceived to be a highly capable, multi-mission platform with the current core crew of 40, the core crew is not able to perform more than one mission at a time (O'Rourke, 2013). With the current manning structure, a LCS can launch and recover helicopters, or launch and recover small boats, but it cannot do both simultaneously (Work, 2013). The OPNAV report by Admiral Perez also points to "significant operational and safety impacts" due to the limited manning structure (Capaccio, 2013).

F. FATIGUE AVOIDANCE SCHEDULING TOOL

FAST is an assessment tool developed for the U.S. Army and U.S. Air Force to aid in fatigue assessment of individual Soldiers and Airmen (Hursh, 2003). FAST can be used to examine an individual's sleep schedule and to predict the resulting level of cognitive effectiveness (Hursh, 2005). Heisinger (2009) and Roberts (2012) used the FAST model to analyze archival sleep data. They demonstrated that FAST accurately predicted the cognitive effectiveness of the individuals in these databases. For this research effort, archival sleep data from individual LCS 2 crew members was input into FAST, which generated a prediction of their cognitive effectiveness. That prediction was compared to actual performance on two standardized cognitive tests, the PVT and the ANAM Switching Test.

G. PSYCHOMOTOR VIGILANCE TESTING

The PVT is accepted in the sleep and neuroscience community as the "gold-standard" for assessing alertness and attention (Pulsar, 2013). The PVT was introduced in the 1980s and has been refined and calibrated, with the added benefit of eliminating learning effects (Basner & Dinges, 2011). While the standard PVT is a 10-minute test, the PVT-B has been developed and tested to be effective in "objectively assessing fatigue-related changes in alertness" (Basner, Dinges, & Mollicone, 2011).

The PVT consists of a yellow box on a black computer screen. The user then presses the spacebar when the box changes to red. The box randomly shifts from yellow to red for the test interval and changes from red to yellow when the spacebar is depressed. The PVT software records the reaction time, as well as the number of times

the user fails to respond to the change (defined as a lapse), and the number of false-starts (pushing the spacebar prior to the box changing color).

Archival PVT data collected from the LCS 2 (USS Independence) were analyzed in this thesis. In this research effort, the PVT data were analyzed to compare actual reaction times in crew member performance (a known indicator of fatigue/sleep deprivation) to the predicted effectiveness from the FAST model.

H. SWITCHING TEST IN AUTOMATED NEUROPSYCHOLOGICAL ASSESSMENT METRICS

The ANAM battery of tests is a collaborative effort between the Department of Defense, the U.S. Army, and the University of Oklahoma (ANAM, 2013). The tests are administered prior to and post deployment for Soldiers in combat zones to help determine the level of cognitive impairment if a Soldier has suffered a Traumatic Brain Injury (TBI) while in combat. Errors can help identify cognitive deficits and help in the determination of fitness for duty of military personnel (Reeves et al., 2007).

For this research effort, the ANAM test used was the Switching Test, which measures executive function and requires visuospatial reasoning, as well as mathematical processing. Figure 3 shows an example of the Switching Test from ANAM.

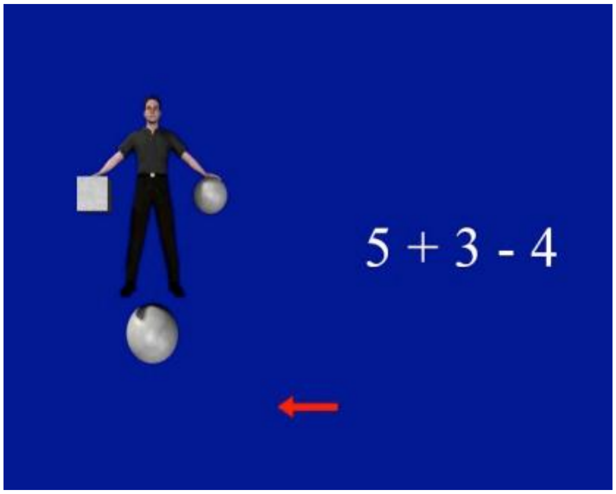

Figure 3. Switching Test from ANAM

III. METHODOLOGY

The first objective of this thesis was to examine the archival sleep and performance data collected on the USS Independence and determine if any relation existed between the collected sleep data and sailor performance on the PVT and Switching Test tests. The second objective was to analyze the sleep data and compare it to the NSWW to provide descriptive information, with the aim of aiding key decision makers in decisions regarding future LCS manning. This chapter describes the methodology used to achieve these objectives.

A. ARCHIVAL DATA FROM USS INDEPENDENCE

The archival data set from the USS Independence was collected during the ship's calm water trials, from May 3 to May 12, 2013, as part of a larger research effort for the Office of Naval Research (ONR) on the LCS program. Thirty-nine crew members participated in the research, 33 males and 6 females, ranging in age from 22 to 40, and naval experience from 1 to 20 years of service. Ten officers and 29 enlisted sailors were in the data set. Of the 39 crew members who participated in the study, only 14 records contained a sufficient number of tests to conduct analysis of the sleep, PVT, and Switching Test data.

1. Data Collection

a. Sleep and Activity Logs

Each sailor was asked to fill out a daily self-reported sleep and activity log during the study period. These data were collected and aggregated into an Excel spreadsheet provided in the archival data set.

b. Actigraphy

Actigraphy was collected using individual actiwatches. Actiwatches are wrist-worn piezoelectric accelerometers that collect information on the wearer's motion and rest patterns (Respironics Inc., 2009). Actiwatches were issued to 31 of the 39 participants and recorded their daily activity and sleep periods for the 10 day test period.

All participants were issued a test ID and the associated serial numbers from issued actiwatches were linked to those participant IDs. Due to incomplete data collection or faulty actiwatches, three records were discarded, which left 28 members having complete sleep data collection for the entire 10-day test period.

c. Performance Testing

Two separate performance tests were conducted as parts of this study, the PVT and the Switching Test. Even though a computer administered both these tests, none of participants was controlled to ensure that the tests were completed at regular or scheduled intervals, which resulting in sporadic and incomplete data for many participants. Of the 28 members who had complete sleep data, only 14 had completed Switching Tests and PVTs on eight days of the 10-day test period. The remaining 14 participant's records were not used in the analysis of the Switching Tests and PVT scores; however, their sleep data were recorded and used in further analysis detailed in the following sections.

2. Data Cleaning

Actigraphy data from the actiwatches were downloaded using Respironics Actiware software. Sleep data from the actiwatches were compared to the self-reported activity logs to ensure that individuals received sleep credit only for those periods when they were actually asleep. The Respironics program uses an algorithm to automatically "score" sleep. These records were cross-checked and reviewed minute-by-minute (defined in the Respironics program as epoch-by-epoch) to ensure that sleep data were as accurate as possible.

3. Export to FAST

After the Actigraphy data were cross-checked against the self-reported activity logs, and the minute by minute review was completed, they were imported into the FAST program and the predicted effectiveness was calculated for each of the 28 members who had complete sleep data.

4. Performance Testing

The data from the performance testing were reviewed to remove any incomplete data. As a result, only 14 members had completed Switching Test and PVTs on eight days of the 10-day test period.

These tests were not administered at controlled intervals and no baseline testing was performed, which further confounded the analysis. To conduct a comparison analysis, it is necessary to have baseline data recorded so that the test data can be compared to the baseline and analyzed for changes. Additionally, PVT and Switching Test testing is normally conducted in a controlled laboratory environment in which distractions are minimized and test intervals rigidly controlled. In a shipboard environment, it may be difficult to eliminate all distractions; however, it is possible to control the test schedule and the number of tests administered, which was not the case for this data set. Analysis was conducted on the available data set and the results are presented with the knowledge that the data were incomplete.

a. PVT

Previous research efforts (Brown, 2012) and previous literature (Basner & Dinges, 2011) stated that the reciprocal mean reaction time on the PVT was the preferred predictor for analysis of PVT performance. The reciprocal MRT is used because it minimizes the least squares error in the regression model.

b. Switching Test

Previous use of the Switching Test has revealed the presence of learning for the duration of the testing (Brown, 2012). One method used to minimize the learning effect is to discard a predetermined number of initial trials. Unfortunately, this data set was limited and discarding any trials would cause the sample size to become too small for meaningful analysis.

5. Institutional Review Board

The proposal for this research effort was submitted to the Institutional Review Board (IRB) of NPS. The IRB application is on file with the NPS IRB office. The IRB determined that the use of archival data was not considered human subjects research and no further IRB action was necessary.

B. ANALYSIS

1. Regression Analysis of Sleep, PVT, and Switching Test Data

The initial analysis of the data was conducted using linear regression with the following predictor and response variables listed in Table 3.

Table 3. Model, response, and predictor variables used in linear regression of sleep, PVT and Switching Test data

Model	Predictor	Response
1	Total Sleep in Minutes	PVT Response Speed (1/MRT)
2	Total Sleep in Minutes	Switching Test Mean Reaction Time
3	Total Sleep in Minutes	Switching Test Throughput
4	Daily Sleep Efficiency	PVT Response Speed (1/MRT)
5	Daily Sleep Efficiency	Switching Test Mean Reaction Time
6	Daily Sleep Efficiency	Switching Test Throughput
7	FAST predicted Effectiveness	PVT Response Speed (1/MRT)
8	Day	Switching Test Mean Reaction Time
9	Day	Switching Test Throughput
10	Day	PVT Response Speed (1/MRT)
11	Day, Day^2	Switching Test Mean Reaction Time

Model	Predictor	Response
12	Day, Day^2	Switching Test Throughput
13	Day, Day^2	PVT Response Speed (1/MRT)

A second analysis was conducted using within subjects ANOVA on the aggregated subject's data to determine the effect of day on the variables listed in Table 4.

Table 4. Model, dependent, and independent variables used in ANOVA of sleep, PVT and Switching Test data

Model	Dependent Variable	Independent Variable
1	Sleep Duration in Minutes	Day
2	Daily Sleep Efficiency	Day
3	Switching Test MRT	Day
4	Switching Test 1/MRT	Day
5	Switching Test Throughput	Day
6	PVT Response Speed (1/MRT)	Day

These models are detailed in the next chapter.

2. Descriptive Statistics of Sleep vs. NSWW

A descriptive analysis of the data set was conducted to examine the deviations between the actual sleep collected through the actiwatches and the sleep recommended in the NSWW. Following previous research by Green (2009), Haynes (2007), and Mason (2009), a chi-square model was used to determine the statistical significance of the deviations.

$$Deviation = \frac{\left(Reported - Allotted\right)^2}{Allotted}$$

The results of this analysis are contained in the following chapter.

IV. RESULTS

A. REGRESSION ANALYSIS

As discussed in the previous chapter, the results presented are for the analysis of the data for those 14 sailors who had complete sleep data, and had taken a sufficient number of performance tests. Switching Test results for sailor M149 on 11 May were removed from the analysis. sailor M149 had results that showed a throughput of 90.37, which meant he was answering the Switching Test questions correctly at a rate of over three per second. This result is unrealistic and was excluded as an extreme outlier.

Regression analysis of the sleep, PVT, and Switching Test data was conducted and the regression models are listed in Table 5. Total sleep in minutes was not found to be a significant predictor of the three measures of performance. Similarly, daily sleep efficiency was not found to be a predictor of the three measures. FAST failed to predict response speed (the inverse of PVT reaction time). In summary, none of the expected predictors of performance was found to vary systematically with the measures of performance.

Table 5. Results of regression analysis of archival USS Independence sleep and performance data

Predictor Variable	Response Variable	β_1	SE β_1	$p(\beta_1)$	r^2
Total Sleep in Minutes	PVT Response Speed (1/MRT)	<0.001	<0.001	.65	.002
Total Sleep in Minutes	Switching Test Mean Reaction Time	0.635	0.541	.24	.013
Total Sleep in Minutes	Switching Test Throughput	-0.002	0.009	.86	<.001
Daily Sleep Efficiency	PVT Response Speed (1/MRT)	0.002	0.001	.09	.024

Predictor Variable	Response Variable	β_1	SE β_1	$p(\beta_1)$	r^2
Daily Sleep Efficiency	Switching Test Mean Reaction Time	5721.	1470.	<.001	.124
Daily Sleep Efficiency	Switching Test Throughput	-46.21	23.44	.05	.035
FAST predicted Effectiveness	PVT Response Speed (1/MRT)	<0.001	<0.001	.91	<.001
Day	Switching Test Mean Reaction Time	-117.19	14.92	<.001	.306
Day	Switching Test Throughput	1.81	0.20	<.001	.431
Day	PVT Response Speed (1/MRT)	<.001	<.001	.45	.005

In contrast, Day (the day the test was taken) is a significant predictor of Switching Test performance. This result is consistent with the interpretation that learning occurred during the administration of Switching Tests. The learning curve apparent in the Switching Test data is detailed in the ANOVA section.

Day (the day the test was taken) did not predict PVT performance, which indicated that the PVT is not subject to learning effects and is likely to be a suitable test for studies of the impact of sleep on performance.

To investigate the learning effect further, Table 6 presents the results of a polynomial model for the data set with Day^2 as the second predictor. The second order model does a better job of predicting the curvature in the Switching Test data. The data shows an asymptote at day seven when the learning effects become insignificant. The implications of this finding suggest that if the Switching Test is to be used in follow-on sleep research, participants should take the test for seven consecutive days prior to the

beginning of data collection to mitigate the learning effects on their individual results. As expected, the polynomial model is not meaningful for the PVT data set due to the lack of learning effect on the PVT.

Table 6. Results of regression analysis of archival USS Independence sleep and performance data

Predictor Variable	Response Variable	β_1	β_2	SE β_1	SE β_2	p(β_1)	p(β_2)	r^2
Day, Day^2	Switching Test MRT	-303.74	17.01	4291.34	-373.08	<.001	<.001	.36
Day, Day^2	Switching Test Throughput	2.70	-0.082	0.802	-0.069	<.001	<.001	.44
Day, Day^2	PVT Response Speed (1/MRT)	<.001	<.001	<.001	<.001	.15	.15	.02

These analyses assume that the factor Day and individual differences were not confounds. These assumptions are tested with ANOVA models as discussed as follows.

1. ANOVA Results

Table 7 presents the summary results of the within-subjects ANOVA on the aggregated subject data, which are detailed in the following sections. Significant differences across participants were found in all analyses. However, controlling for individual differences did not change any of the conclusions drawn from the regression analyses. As seen from inspection of Table 7, some of the ANOVA, show significant results (Switching Test MRT and Switching Test Throughput) while sleep duration, sleep efficiency, and PVT Response Speed do not show significant results.

Table 7. ANOVA summary table of the sleep, PVT, and Switching Test data

Model	Dependent Variable	Independent Variable	dF	F	p(F)
1	Sleep Duration in Minutes	Day	(9,111)	1.68	.10
2	Daily Sleep Efficiency	Day	(9,111)	1.18	.31
3	Switching Test MRT	Day	(9,90)	8.29	.00
5	Switching Test Throughput	Day	(9,90)	21.83	.00
6	PVT Response Speed (1/MRT)	Day	(9,100)	0.77	.65

Due to empty cells in the data matrix for multiple sailors, the mean square error was inflated. This inflation ranged from 0.3% on the daily sleep duration ANOVA to 10.8% on the Switching Test MRT ANOVA.

The ANOVA results show that sleep duration and efficiency do not vary systematically with day. Accordingly, the aggregation of the data set across day in the regression analyses is valid.

a. Individual ANOVA results

(1) Sleep Duration and Day. The results of the analysis of sleep duration as a function of day, Table 8, show the amount of sleep sailors received was not dependent on day. Clear individual differences occurred in sleep duration.

Table 8. Sleep duration as a function of day

	SS	df	MS	F	prob
Treatments	122070.4	9	13563.4	1.68	0.1025
Within	1356170.8	124			
Subjects	464021.0	13	35693.9	4.42	0.0000
Error	897097.9	111	8082.0		
Total	1483189.3	133			

Figure 4 provides a graphical display of the average daily sleep duration across all days. A decline on average occurs but no clear pattern exists. *Post hoc* analysis showed that sailors received significantly less sleep on May 7 and more sleep on May 3.

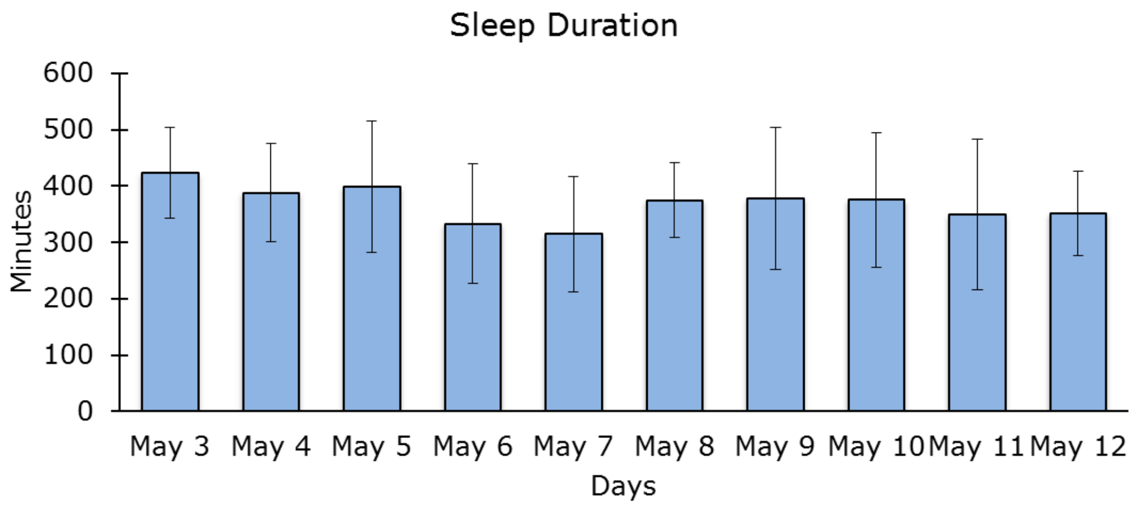

Figure 4. Average daily sleep in minutes across all days

(2) Sleep Efficiency and Day. The results of the analysis of sleep efficiency as a function of day, Table 9, show that the efficiency (quality) of sleep sailors received was not dependent on day. Clear individual differences occurred in sleep efficiency.

Table 9. Daily sleep efficiency as a function of day

	SS	df	MS	F	prob
Treatments	0.01	9	0.001	1.18	0.3131
Within	0.18	124			
Subjects	0.10	13	0.008	9.74	0.0000
Error	0.09	111	0.001		
Total	0.20	133			

Figure 5 provides a graphical display of the average daily sleep efficiency across all days. No clear pattern exists. *Post hoc* analysis shows that sleep efficiency was highest on May 3 and was significantly greater than on May 5, 6, 9, and 12. No other *post hoc* differences were significant.

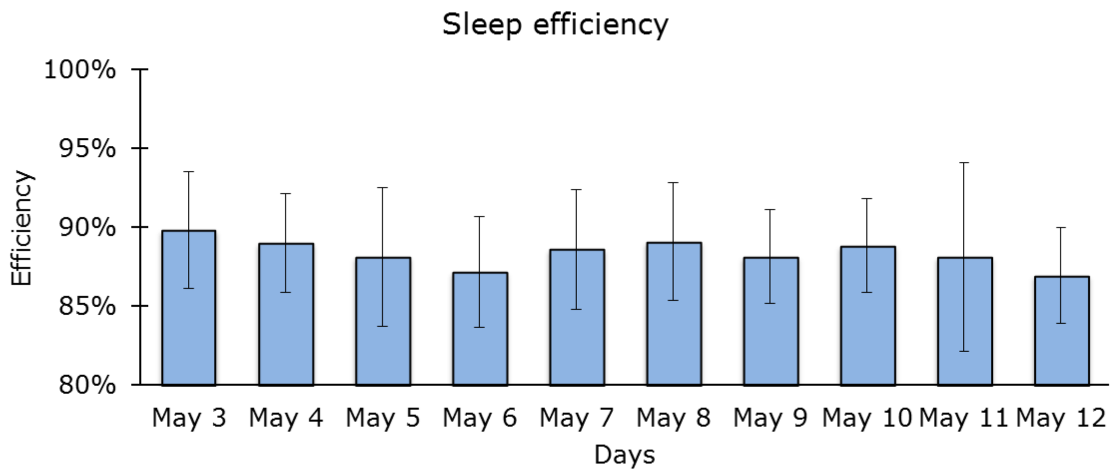

Figure 5. Average daily sleep efficiency across all days

(3) Switching Test MRT and Day. The results of the Switching Test MRT as a function of day ANOVA shows that day is a significant predictor of performance on the Switching Test. Table 10 shows the ANOVA results.

Table 10. Switching Test mean reaction time as a function of day

	SS	df	MS	F	prob
Treatments	12926418.7	9	1436268.7	8.29	0.0000
Within	33356180.5	103			
Subjects	24940502.3	13	1918500.2	11.08	0.0000
Error	15590234.1	90	173224.8		
Total	53457155.1	112			

Figure 6 illustrates that learning effects are present within the Switching Test results. These results contain an error term of 10.8% due to empty cells, which suggests a lack of rigor in the experimental protocol. *Post hoc* analysis showed

that the learning effect was statistically significant from May 3–May 6, which implies that if the Switching Test is going to be used, it should be administered daily for seven days prior to the beginning of experimental data collection.

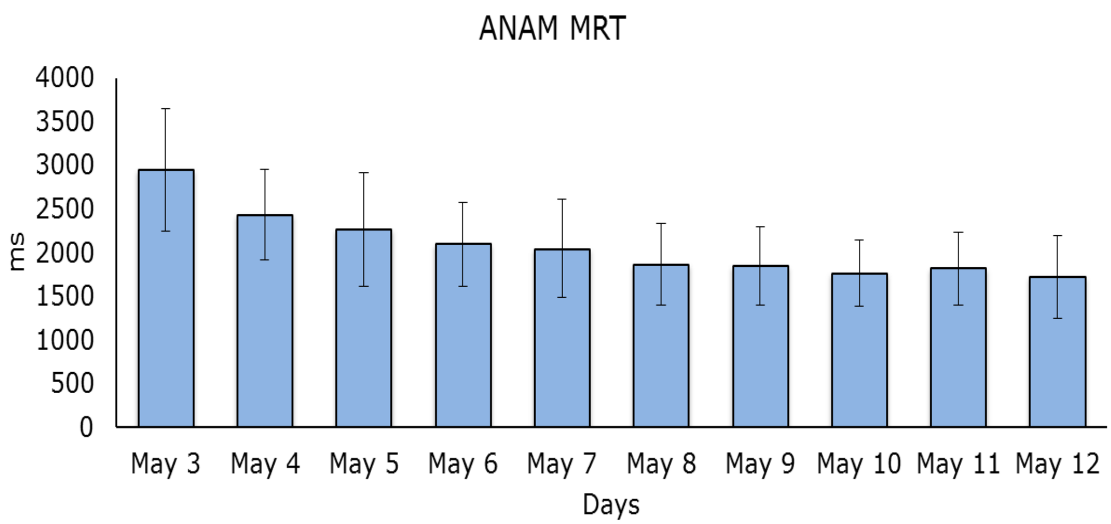

Figure 6. Switching Test MRT by day

(4) Switching Test Throughput and Day. The results of the Switching Test Throughput as a function of day ANOVA shows that day is a significant predictor of Switching Test performance. Table 11 shows the ANOVA results.

Table 11. Switching Test throughput as a function of day

	SS	df	MS	F	prob
Treatments	2206.3	9	245.1	21.83	0.0000
Within	7180.8	103			
Subjects	6503.6	13	500.3	44.55	0.0000
Error	1010.6	90	11.2		
Total	9720.5	112			

Figure 7 illustrates that learning effects are present within the Switching Test results. These results contain an error term of 3.4%. *Post hoc* analysis showed that the learning effect was statistically significant from May 3–May 8, which

suggests that if the Switching Test is going to be used, it should be administered daily for seven days prior to the beginning of experimental data collection.

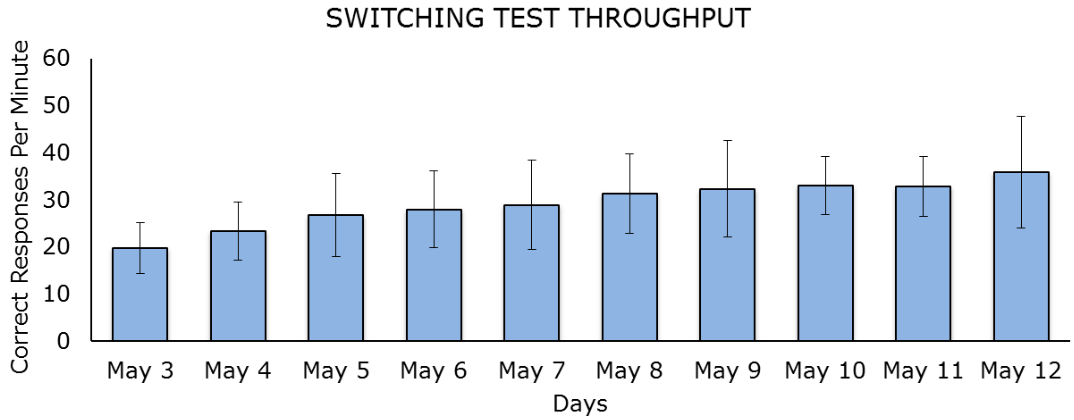

Figure 7. Switching Test throughput by day

(5) PVT Response Speed (1/MRT) and Day. The results of the analysis of PVT Response Speed as a function of day, Table 12, show the PVT Response Speed was not dependent on day. Individual differences occurred in PVT Response Speed.

Table 12. PVT response speed (1/MRT) as a function of day

	SS	df	MS	F	prob
Treatments	0.0	9	0.0	0.77	0.648563
Within	0.0	113			
Subjects	0.0	13	0.0	7.75	0.000000
Error	0.0	100	0.0		
Total	0.0	122			

Figure 8 provides a graphical display of the average PVT Response Speed across all days. No clear pattern exists and no indications of learning are present.

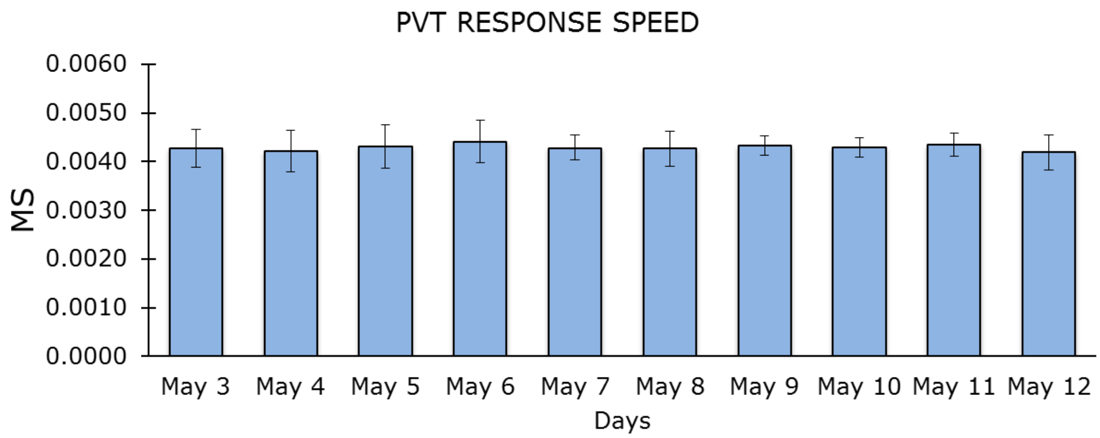

Figure 8. PVT response speed by day

B. ACTIGRAPHIC SLEEP VS. NSWW RECOMMENDATIONS

The actigraphic sleep was compared to the recommended (allotted) sleep from the NSWW using a chi-square test. The NSWW standard is 480 minutes per day.

$$Deviation = \frac{(Reported - Allotted)^2}{Allotted}.$$

The chi-square test suggests a significant departure from the expected daily sleep time of 480 minutes daily, chi-square (249) = 12239, p <.0001.

Table 13 shows the number of minutes above or below the daily NSWW sleep recommendation with cumulative totals by day and sailor listed. The data show that all but one sailor was sleep deprived every day. Of note in these totals are the results from May 7 when the crew experienced a total of 4,056 minutes (67.6 hours) of sleep loss. The total daily deficit of only 1,353 minutes (22.5 hours) on May 3, 2013 is also of note. May 3 was a Sunday. Ship's crews are traditionally granted "holiday routine" on Sundays while underway. A "holiday routine" means a sailor not actively standing watch is allowed to sleep. Sundays have traditionally been the day when the crew attempts to catch up on their weekly sleep deficit. Even though the crew of LCS-2 attempted to catch up on this deficit, the crew was still 22.5 hours short.

Table 13. Daily minutes above or below NSWW sleep recommendation

Sailor	Date 5/3	5/4	5/5	5/6	5/7	5/8	5/9	5/10	5/11	5/12	Total	Ave	Cumulative
M101		64	-24	-90	-137	-86	-90	-128	-93	-154	-738	-82	-738
M103	-197	-87	-141	-84	-257	-93	-232	-275	-185	-188	-1739	-174	-2477
M105	-55	-43	-222	-379	-97	-167	-59	-136	-139		-1297	-144	-3774
M106	-45	-43	-39	-105	-33	-91	49	-89	99		-297	-33	-4071
M109	-480	34	-9	76	-68	-75	-69	-35	-48	-77	-751	-75	-4822
M110	-266	-36	-143	-40	-300	-166	-99	69	-303	-275	-1559	-156	-6381
M111	-19	-204	-142	-118	-188	-196	-86	-116	-178	-76	-1323	-132	-7704
M113	-57	-210	-162	-176	-258	-134	-199	-237	-289	-68	-1790	-179	-9494
M114	-13	-122	-137	-213	-236	-161	-331	-41	-341	-130	-1725	-173	-11219
M115		-184	-82	-418	-315	-290	-318	-393	-246	-241	-2487	-276	-13706
M116	-10	-192	70	-17	-43	-53	-19	-155	-92	-28	-539	-54	-14245
M117	-203	-167	65	80	24	-76	73	-66	-104	-20	-394	-39	-14639
M118	-196	113	130	68	-98	-10	-76	-5	22	-203	-255	-26	-14894
M119	47	54	50	67	-120	10	-118	-68	-236		-314	-35	-15208
M120	-152	-221	-210	-179	-335	-73	-222	115	-145		-1422	-158	-16630
M121	-8	-61	69	-89	-76	-122	96	-95	-76	-127	-489	-49	-17119
M123	-162	-310	-66	-222	-300	-173	-185	-271	-68		-1757	-195	-18876
M125	-96	-72	-187	-177	-64	-223	-149	-173	-73	-48	-1262	-126	-20138
M127	-49	62	73	-1							85	21	-20053
M128		-95	-51	-137	-155			-254	-247	-156	-1095	-156	-21148
M129	38	-108	-17	28	-12	-31	-41	-354	123	-184	-558	-56	-21706
M132	-58	-16	32	-63	-156	-20	3	-41	-129		-448	-50	-22154
M145	-71	-226	-7	25	-113	76	-77	-235			-628	-79	-22782
M146	-100	-145	-60	50	-237	-135	-214	2	-213	-93	-1145	-115	-23927
M147	-3	4	167	-110	-47	25	-7	-59	-71	-2	-103	-10	-24030
M148		-118	-202	-229	-225	-173	-139	-229	-94	-96	-1505	-167	-25535
M149	-43	-165	-108	-290	-210	-69	-301	-122	-186	-169	-1663	-166	-27198
Total	-2198	-2494	-1353	-2743	-4056	-2506	-2810	-3391	-3312	-2335			
Ave	-98	-90	-48	-94	-154	-102	-105	-131	-130	-120			
Cumulative	-2198	-4692	-6045	-8788	-12844	-15350	-18160	-21551	-24863	-27198			

Of the 250 sleep observations, only 36 (14.4%) were above the daily recommendation of 480 minutes. The only sailor with a positive cumulative total was sailor M127, whose sleep data was recorded only for the first four of the 10-day test period. The average sleep loss per day for all sailors was 109 minutes (1.81 hours) with a standard deviation of 112 minutes (1.86 hours).

The most severe sleep loss observed was for sailor M115, who had an observed total sleep deficit of 2,487 minutes (41.45 hours) for the 10-day test period. sailor M115 stood watch as the readiness control officer (RCO) who monitors the LCS engineering plant, and is responsible for the proper operation of the ship's electrical, propulsion, and auxiliary equipment. The FAST predicted effectiveness shown in Figure 9 shows that sailor M115 spent nearly 80 percent of the underway period with a predicted

effectiveness below 70 percent. The equivalent B.A.C. is 0.08, which is legally intoxicated in all 50 states. No commanding officer would ever allow an intoxicated sailor to stand watch, particularly a station as critical as RCO.

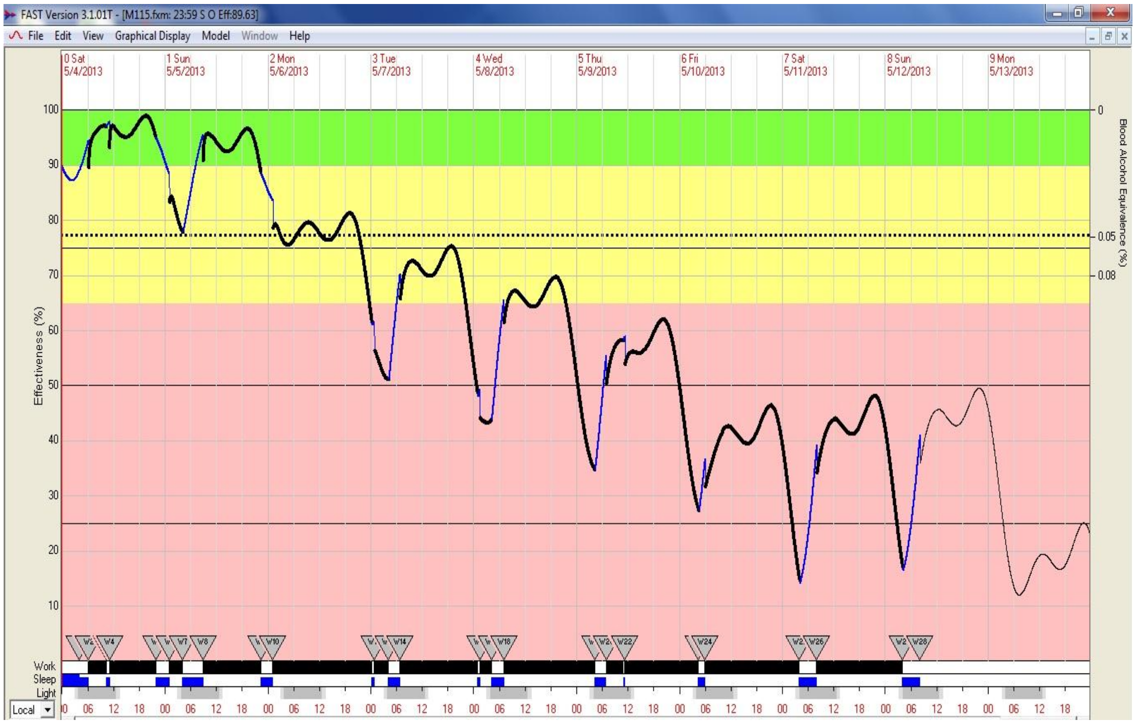

Figure 9. FAST output for sailor M115

Figure 10 is a histogram showing the number of sailors and their total minutes of sleep above or below the recommendation in the NSWW for the 10-day test period. Sailor M127 was the only positive value but had data for only four days.

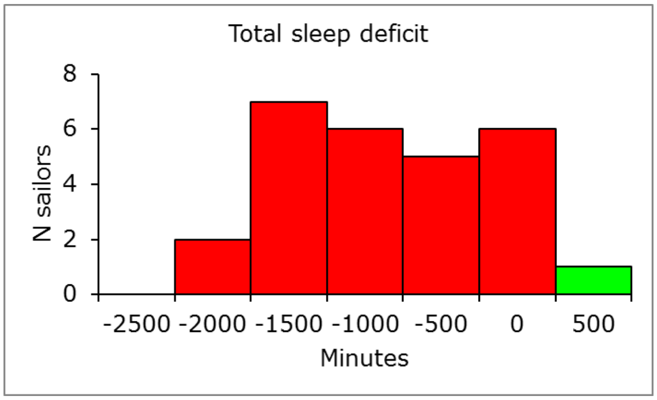

Figure 10. Number of sailors and their number total minutes of sleep above or below the recommendation in the NSWW

C. MODEL OF FAST PREDICTED EFFECTIVENESS AND PVT MEAN REACTION TIMES

Regression was used to examine the relationship between the predicted effectiveness from FAST and the PVT MRT. The regression model was expected to make it possible to estimate an individual's reaction time based on their predicted effectiveness from the FAST model. The lack of rigor in experimental protocol resulted in limited data. Accordingly, the regression analysis did not yield significant results, and did not allow for the construction of a meaningful predictive model. These data do not support the prediction of sailor PVT performance using FAST output.

V DISCUSSION

At the heart of any research is the "why do we care" question. In spite of hundreds of sleep studies and years of documented research, the issue of crew fatigue and sleep deprivation continues to plague the U.S. Navy and the Department of Defense. The answer should be as simple as "it's the right thing to do, to care for our people and to maximize their ability to perform by ensuring they have adequate rest," in the same way that the Navy ensures an officer's ability to fly a jet, or take control as officer of the Deck while underway. However, the issue is not that simple. Unique operational requirements and the incredible strain during the fog of war make it an extremely complicated calculus.

From the perspective of a surface warfare officer, the argument can be made that the Navy has spent hundreds of billions of dollars on the latest technologies and training for the AEGIS weapons system. Yet, in spite of the remarkable technological advancements, the system is still only as good as its operators. Certainly, features of the system remove much of the human element but while the "man is in the loop," any delay in the reaction times of weapon system operators equates to lost battle space. That lost battle space can mean the difference between firing in time to neutralize the inbound threat, or becoming the latest "Fox News Alert."

A basic open-source analysis of the battle space lost yields an outcome that should make any Surface Warfare Commander worth their salt take notice. If four operators are required to fire ordnance at an inbound threat, and each of those operators has a delay of as little as 250 ms, then the crew has lost as much as one second of battle space. Increasing that delay to 350 ms means the crew loses 1.4 seconds. Recent research on the USS Jason Dunham has shown that the individual sailor delays were averaging closer to 750 ms (Young, 2013). An average delay of 750 ms produces a total loss of three seconds of battle space.

Table 14 lists some of the most common Anti-Ship Cruise Missiles (ASCM) (taken from Wikipedia) around the world and the battle space lost is 1.0, 1.4, and 3.0 seconds.

Table 14. Battle space lost due to operator delay

Missile	Speed/Second	Feet (Miles) of Battle Space Lost in 1 Second	Feet (Miles) of Battle Space Lost in 1.4 Seconds	Feet (Miles) of Battle Space Lost in 3 Seconds
Exocet	1030	1030 (0.20)	1442 (0.27)	3090 (0.59)
Sunburn	2551	2551 (0.48)	3571.4 (0.68)	7653 (1.45)
Sizzler (sprint)	3200	3200 (0.61)	4480 (0.85)	9600 (1.82)
STYX	1000	1000 (0.19)	1400 (0.27)	3000 (0.57)
C-802	1000	1000 (0.19)	1400 (0.27)	3000 (0.57)
Kayak	900	900 (0.17)	1260 (0.24)	2700 (0.51)

Table 14 illustrates the potentially severe consequences resulting from crew fatigue, and the inherent danger presented to the crew.

Looking at the issue through the lens of Reason's Swiss Cheese Model of Human Error (Reason, 1990), it can be argued that the holes in the lenses of the "Swiss cheese" model, particularly in the ACTS lens, get larger as fatigue increases. Figure 11 provides a simplified view of Reason's Swiss Cheese Model for Human Error with the black holes representing the normal condition of human errors, with a well-trained, well-equipped, and well-rested crew/operator. In this scenario (represented by the black line), the holes do not align and no incident occurs. In the second scenario (represented by the red line and circles) with the same well-trained and well-equipped crew/operator who is now fatigued, the holes are much larger and the likelihood of an incident is increased.

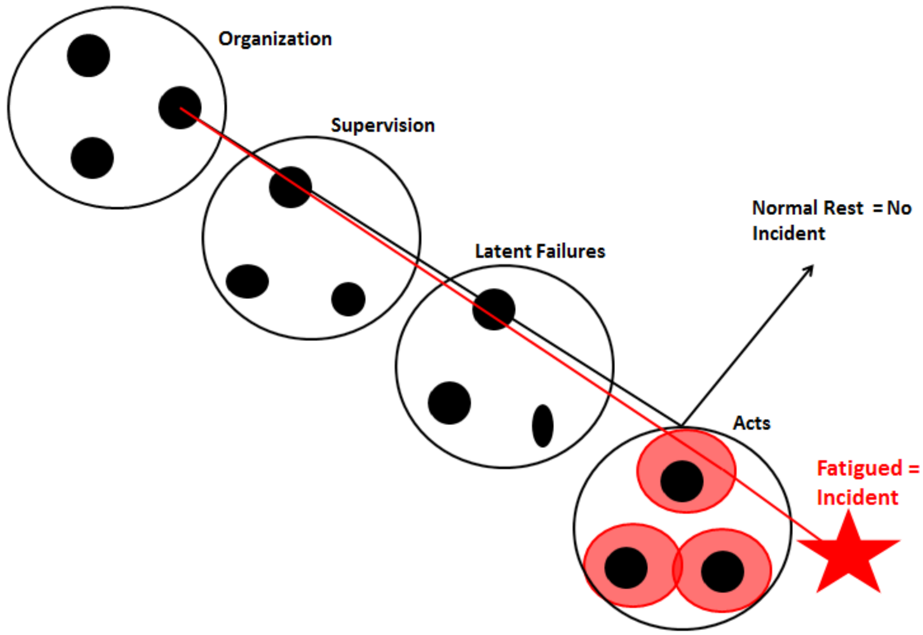

Figure 11. Reason's Swiss cheese model of human error with fatigue added

Previous research has illustrated that cognitive functioning and executive decision making are affected by fatigue (McKenna et al., 2007; Nilsson et al., 2005). Applying that knowledge to the Dynamic Model of Situated Cognition (Miller & Shattuck, 2006), it is easy to see how fatigue affects a decision maker's perception and can lead to errors or worse to incidents and accidents. Figure 12 shows the Dynamic Model of Situated Cognition developed by Miller and Shattuck (2006).

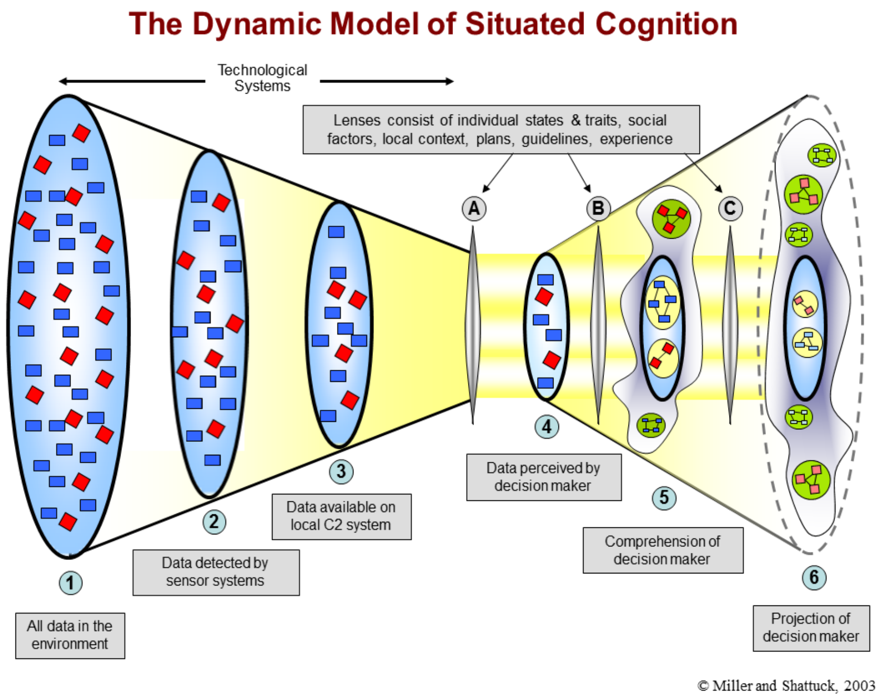

Figure 12. The dynamic model of situated cognition (From Miller & Shattuck, 2006)

Even in the best-trained, best-equipped, and most well-rested decision makers, the lenses (A, B, and C in Figure 12) are subject to the unique states and traits of those individuals. When they are fatigued, those lenses are fogged by that fatigue and the perception of the reality around them, as well as their ability to make critical, time-sensitive decisions is slower, or in the worst cases, non-existent.

The fogging of these lenses can also lead to consequences outside the operational or war fighting arena. Killgore (2006) found that moral judgment is also impaired by fatigue. Research has also equated fatigue to an equivalent B.A.C. level (Dawson & Reid, 1997; Lamond & Dawson, 1999). Combining these two known factors, it can be reasonably assumed that when a fatigued sailor reaches port after weeks or months of arduous operational tasking, judgment and decision-making abilities are diminished. If alcohol is added to the equation, the consequences of that fatigue grow exponentially.

Given the reported sleep data from the 10-day underway period for LCS-2, it is reasonable to assume that these issues would be seen during a deployment or extended underway period. Follow-on research is needed to determine which watch stations and

positions within the crew are most affected by interaction of fatigue and the limited manning concept. A suggested course of action for this research effort is presented in the next chapter.

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VI. CONCLUSIONS AND RECOMMENDATIONS

A. EFFECTS OF FATIGUE ON CREW PERFORMANCE

Based on the results of this study, it is clear that the crew of LCS-2 is not obtaining enough sleep and is subject to the effects of extreme fatigue. Unfortunately, the lack of usable data in the archival data set failed to yield meaningful regression models. The presence of learning in the Switching Test results caused the results to be an inappropriate metric for a repeated measures design. A set of baseline PVT tests for comparison purposes was not collected. The lack of ship's schedule and employment information (obtained from watchbills/plans of the day/plans of the week) made cross-checking of the self-reported activity logs cumbersome and led to holes in the schedule.

The day-to-day operations of a U.S. Naval warship can be unpredictable and conditions on the open ocean can change rapidly. However, the holes in the data set were indicative of a systematic failure to exercise the level of scientific rigor necessary to obtain data that would contribute to finding solutions for the issue of crew fatigue. The following section provides recommendations for a follow-on study that has the promise to provide a significant amount of useful data that may lead to meaningful results.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

Even in the most stringently controlled laboratory environment holes and inaccurate data are likely to be recorded during the course of a study. The challenges of "real-world" data collection are well known (Johnson & Milliken, 1984), and the roadblocks to collection can be exponentially exacerbated onboard a ship at sea. Evolving schedules and unpredictable weather and sea conditions can affect even the most well-designed and well-executed studies. In spite of these known and unknown obstacles, the following is suggested as a course of action to obtain a significant amount of data that has the potential to yield meaningful results in follow on sleep studies conducted on Naval vessels.

While analysis of the archival data set from LCS-2 failed to yield statistically significant results, it was apparent that the use of actiwatches, PVT, and self-reported activity logs provided useful information. The use of the Switching Test showed that learning effects were present and precluded meaningful results for the purposes of this study. If the Switching Test is to be used in follow-on research, it is recommended that the test be administered on seven consecutive days prior to data collection to allow the learning effects to be mitigated.

The lack of baseline PVT and Switching Test data did not allow comparisons to be made and were a key contributor to the failure to test the hypothesis that PVT and Switching Test performance would be affected by fatigue. An infinite number of uncontrolled variables are in the collection of baseline sleep data collected in a non-clinical environment; however, it is recommended that a minimum of 14 days of baseline data be collected prior to an at sea period. Unfortunately, operational commitments often occur the weeks and days prior to a warship taking to sea that cause these periods to be more stressful than the actual at sea operations. This complication requires researchers to have a cursory knowledge of ship operations and schedules, and it is recommended that a ship be selected that is not subject to an inspection or demonstration prior to the underway period.

The use of, and the information collected from, actiwatches has been a key to previous sleep research. The use of this technology is critical to the success of future sleep research. It is recommended that the data from the watches be downloaded into Respironics (or similar software) daily during the duration of the sleep study. During this download, it is also recommended that researchers review the daily self-reported activity log with the study participants to verify the accuracy of the log. In addition to the self-reported activity logs, it is further recommended that all watchbills and plans of the day and week be collected to cross-check the actiwatch data and the self-reported logs.

Along with the basic demographic data collected (age, sex, rank), it is critical to list the department, division, and name of the watch station that an individual study participant holds. If the participant has a specific collateral duty, such as being a member of the ship's Flight-Quarters or Vessel Boarding Search and Seizure (VBSS) team, that

information is critical to the cross-check and validation of schedules to provide the most accurate accounting of an individual's time at sea. Previous sleep studies (Yokeley, 2012) have focused on specific watch rotations or the effect of sea conditions (Brown, 2012). The focus of a research effort is not specific to these recommendations. However, the accurate collection of schedule data is critical for proper analysis.

Although regression analysis of this LCS-2 archival data set failed to provide meaningful results to test the hypothesis that PVT performance would be negatively affected by increased fatigue, it is recommended that the PVT continue to be administered as part of an overall sleep study. The administration of the PVT needs to be controlled and the number and schedule of PVTs be monitored. It is recommended that PVTs be administered at specific intervals for study participants and an equal number of tests be administered to all participants. Some participants cannot or will not likely complete all tests; however, scientific methods and rigor should be emphasized in any follow-on study.

While funding and schedule constraints may preclude a study from taking place over an extended period, it is recommended that follow-on studies last for a minimum of 14 days, and preferably, 28 days. Ideally, testing should begin on a Monday and end on a Sunday, and include "holiday routine" schedules (only) on Sundays. The involvement and support of a ship's Chief's Mess, training officer, department heads, executive and commanding officers is vital to a successful study at sea.

These recommendations are applicable across all ship platforms and classes, and represent the ideal scenario. Under current funding conditions, it is likely that it will be difficult to find a ship heading to sea without an inspection or demonstration period, and the duration of a sleep study may be limited to less than the recommended 28-day cycle. In spite of these issues, the accurate collection of schedule data and an adherence to proper scientific protocol is critical to study success.

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